Modelling land based nutrients relating to *Lyngbya majuscula* (Cyanobacteria) growth in Moreton Bay, southeast Queensland, Australia

S.M. POINTON
Queensland Department of Natural Resources and Water, Indooroopilly, Brisbane, Qld 4068, Australia. Email: Shane.Pointon@nrw.qld.gov.au

K.S. AHERN
University of Queensland, Water Studies, Environmental Engineering, Brisbane, Qld 4072, Australia

C.R. AHERN
C.M. VOWLES
V.J. ELDERSHAW
Queensland Department of Natural Resources and Water, Indooroopilly, Brisbane, Qld 4068, Australia

M. PREDA
Queensland University of Technology, Brisbane, Qld 4001, Australia

Citation: Pointon, S.M., Ahern, K.S., Ahern, C.R., Vowles, C.M., Eldershaw, V.J. & Preda, M. 2008 12 01. Modelling land based nutrients relating to *Lyngbya majuscula* (Cyanobacteria) growth in Moreton Bay, southeast Queensland, Australia. *In*, Davie, P.J.F. & Phillips, J.A. (Eds), Proceedings of the Thirteenth International Marine Biological Workshop, The Marine Fauna and Flora of Moreton Bay, Queensland. *Memoirs of the Queensland Museum — Nature* 54(1): 377–390. Brisbane. ISSN 0079-8835.

ABSTRACT

Moreton Bay, in southeast Queensland, experiences seasonal blooms of the cyanobacterium, *Lyngbya majuscula*. Mounting evidence suggests nutrients can increase the intensity and severity of *L. majuscula* blooms when environmental conditions are favourable. The main 'nutrients' of concern, are bio-available iron, phosphorus, nitrogen and dissolved organic carbon. The current study used a GIS-based model to generate a map identifying areas most likely to supply/export nutrients of concern to Moreton Bay. Based on GIS coverages (acid sulfate soils, landuse, soils, groundwater, pre-clearing vegetation and remnant vegetation) and a proximity to coasts and streams coverage (to weight the likelihood of export), parcels of land were ranked for hazard and compiled into a nutrient hazard model. The model was initially developed in a reference area (46,000ha) supported by field investigations, soil analyses and *L. majuscula* bioassay and laboratory analysis of groundwaters. The map outputs compared favourably with soil analyses from > 80 sites collected following model development. The model was extended beyond the reference area to produce an indicative nutrient hazard map of coastal Southeast Queensland (2.3 million ha). The model and resulting maps from this investigation provide an areal assessment of where to concentrate efforts to limit or reduce nutrient loads that may contribute to *L. majuscula* blooms. Maps produced from earlier modelling have been used to support a new *Algal Blooms policy 2.4.7* within the *Southeast Queensland Regional Coastal Management Plan* (EPA, 2006) and versions in this paper provide an update. Appropriate nutrient management guidelines need to be developed for industry use when disturbing areas rated high or very high in the nutrient hazard maps. ☐ *acid sulfate soils, bio-available iron, cyanobacteria, dissolved organics, GIS, nitrogen, phosphorus, nutrient hazard map*

Coastal waters worldwide appear to be experiencing an increase in the occurrence of harmful algal blooms (Paerl 1988; Paerl & Fulton 2006). In particular, the cyanobacterium *Lyngbya majuscula* has been causing a nuisance in coastal waters and reef environments worldwide (Dennison *et al.* 1999; Albert *et al.* 2005), including along the coast of Queensland (Albert *et al.* 2005). Blooms in Moreton Bay, have increased in size, frequency and severity since the early 1990's (Dennison *et al.* 1999; Ahern *et al.* 2007b).

Lyngbya majuscula (family Oscillatoriaceae) is a toxic (see review in Osborne *et al.* 2001), filamentous, benthic cyanobacterium that grows in close association with the sediment, or epiphytically on seagrass, macroalgae or corals (Dennison *et al.* 1999). It appears to be a common, non-dominant component of many shallow subtropical and tropical marine ecosystems (Diaz *et al.* 1990) but also can undergo explosive growth and areal expansion forming mono-specific blooms that overgrow and smother intertidal and subtidal benthic communities (Watkinson *et al.* 2005).

The rapid proliferation of cyanobacteria blooms requires the availability of the macronutrients nitrogen (N) and phosphorus (P), and micronutrients including iron (Fe) which regulate photosynthesis and ultimately growth. As *L. majuscula* has the capacity to fix N, it is less likely that growth will be limited by low N availability (Diaz *et al.* 1990; Lundgren *et al.* 2003), as is common for marine plants in many tropical and subtropical environments including Moreton Bay, Queensland (e.g. O'Donohue & Dennison 1997). Instead, laboratory studies have shown P (Kuffner & Paul 2001; Elmetri & Bell 2004; Ahern *et al.* 2007a), bio-available Fe (Gross & Martin 1996; Ahern *et al.* 2006b, 2007a), and to a lesser extent molybdenum (Mo) (Ahern *et al.* 2006b) are important for growth, photosynthesis and N fixation of *L. majuscula*. These results have been confirmed by in-situ field studies in eastern (Ahern *et al.* 2007a) and north-western Moreton Bay (Deception Bay) (Ahern *et al.* 2008a), where prolific growth of *L. majuscula* has resulted when bio-available Fe, P and N were added to the water column.

Organic matter (such as humic and fulvic acids found in runoff from coastal catchments) also appears to play an important role as a chelating agent, complexing and maintaining solubility of Fe and/or P in the slightly alkaline seawater (Rose & Waite 2003). This has the effect of increasing the availability of Fe, and to a lesser extent P, to *L. majuscula* (Ahern *et al.* 2006b). Organic matter formed from pine plantations has shown to be a particularly strong complexor (Rose & Waite 2003).

Soil and groundwater pH can strongly influence the leaching ability and solubility of nutrients. Fe in particular (McKenzie *et al.* 2004), but also most P minerals and compounds are more soluble under acidic conditions. Coastal sandy sediments are commonly acidic and have little ability to retain nutrients. Another soil group, termed acid sulfate soils (ASS), contain iron disulfides, mainly pyrite, and sometimes iron monosulfides that on exposure to air from disturbance or drainage, produce large quantities of acid and Fe. ASS can vary from sand through to fine textured clay and marine muds. The acidic conditions maintain Fe solubility, thus large quantities of Fe can be exported from the area via ground or surface waters. ASS commonly occur along drainage lines or close to the coast, and as they are common in south eastern Queensland their impact on inshore waters can be significant.

Given the rapid population growth along coastal southeast Queensland (Graymore *et al.* 2002), coastal catchment activities must be carefully managed to limit or reduce the supply and transport of bio-available nutrients to waterways and coastal waters. If nutrient inputs continue to increase, then seasonal *L. majuscula* blooms are likely to be larger, and their impacts more severe. Different parts of the catchment have different nutrient compositions and quantities, and vary also in their ability to export/transport bio-available nutrients to waterways and/or groundwaters. Thus the exact sources of nutrients, and the transport pathways to *L. majuscula* bloom sites, need to be accurately determined. The aim of the present study was to create a model that would produce map outputs showing areas that have the potential to supply/export nutrients to coastal waters in southeast Queensland at levels that could accelerate *L. majuscula* growth.

MATERIALS AND METHODS

STUDY AREA

The meso-scale (detailed reference area) modelling and field assessment involved the area (approx. 46,000ha) from Scarborough to Donnybrook. Following the trial of the methodology on the 'reference area' (meso-scale maps) the methodology was extended to the whole area (macro-scale map). The macro-scale (broad scale) modelling encompassed the coastal areas (approx. 2,257,000ha) from the Queensland/ New South Wales border (28°10' lat.) to Eumundi (26°45'lat.) and was bounded on the west by the Great Dividing Range. It included the following major catchments: Brisbane River, Logan River, Pine River, Caboolture River, Maroochy River, Mooloolah River and the Pumicestone Passage and Gold Coast catchments.

EXISTING GIS COVERAGES

Multiple GIS coverages (ASS, landuse, soil, groundwater, pre-clearing vegetation, and remnant vegetation) were included in the model to enable integration of different factors (such as soil, vegetation and landuse type) that are known to impact on the ability for different parcels of land to store and/or supply nutrients. Based on current understanding of the nutrients required for *L. majuscula* growth, these GIS coverages were identified as being the best combination to indicate areas of potential nutrient storage and supply. However they have been reinterpretated in this paper to make the parameters specifically apply to modelling of nutrient sources.

An additional GIS coverage was developed to indicate proximity to coasts and streams. Our model could thus take into account both the intrinsic nutrient storage capacity of a particular parcel of land as well as its potential to supply and export those nutrients to estuarine and near coastal environments.

ASS coverage. Macro-scale data were compiled by NRW (Queensland Department of Natural Resources and Water) during a number of projects in the area. Mapping scales range from 1:25 000 to 1:100 000. A rating of 1 was assigned to areas not assessed during ASS survey. The sand islands of Moreton Bay were given a rating depending on the topography and geology, since only limited field-testing of the soils has been carried out. The highest rating of 4 was restricted to actual ASS areas (where field pH is <4.0), due to their known potential to release Fe.

Land use coverage. Digital land use maps as at 1999, at a nominal scale of 1:50 000, were available for the catchments of Brisbane, Logan and Albert Rivers, south coast streams (i.e. Gold Coast), Pine Rivers, Pumicestone Passage rivers and streams (including the Caboolture River), and the Maroochy and Mooloolaba Rivers (NR&M 2005a). Land use is classified according to the Australian Land Use and Management Classification (ALUMC) version 5, November 2001.

Land uses that were given a high rating of 3 or 4 included areas where:

- large amounts of fertiliser are regularly applied, e.g. agriculture.

Table 1. Details of soil surveys used in the GIS 'soil coverage'.

Organisation	Survey study area	Scale
NRM&E	Brisbane Valley land resource survey	1:50 000
NRM&E	Lockyer valley land resource survey	1:50 000
NRM&E	Soils and land suitability — Albert River, Chardons Bridge to Boylands	1:50 000
CSIRO	Soils and land use in the Beenleigh–Brisbane area	1:50 000
CSIRO	Soils of the Brisbane and south east environs	1:50 000
QDPI	Horticultural land suitability survey — Sunshine Coast	1:100 000
QDPI	Moreton region land management field manual	1:100 000
CSIRO	Atlas of Australian soils	1: 2 000 000

Table 2. Broad categories of dominant aquifer material used to develop the groundwater coverage (adapted from Preda & Cox 2004). Hazard ratings for each category for the five nutrients are shown in the last five columns.

	Dominant aquifer material	Hydraulic conductivity (m/day)	Fe content (mg/L)	References	Ratings				
					Fe	P	OC	pH	N
A	Igneous rocks	0.0001			1	1	1	1	1
B	Sandstone	0.01	0–3	Harbison & Cox 2002; Armstrong & Cox 2002; Ezzy *et al.* 2002	2	1	2	1	2
C	Basalt	2.50	0–2	Locsey, 2003; Barclay, 1997	2	1	3	1	3
D	Alluvial sediments adjacent to 2 (>10m AHD)	5.00	0–5	Wilson (unpub. data)	3	1	4	2	4
E	Alluvial sediments adjacent to 3 (>10m AHD)	5.00			3	1	4	2	4
F	Marine deposited sandy sediments (<10m AHD)	6.50	0–20	Armstrong & Cox, 2002	4	1	4	3	4
G	Marine deposited fine-grained sediments (<10m AHD)	0.10	1–35 10s–100s	Harbison & Cox 2002; Ezzy *et al.* 2002; Lee *et al.* 2002	4	1	2	4	2

- frequent soil disturbance occurs, e.g. extractive industries.
- large quantities of nutrients are produced and exported, e.g. sewage treatment plants, intensive agriculture.
- high levels of natural nutrient are present, e.g. coastal wetlands.

General soils coverage. Data from various soil mapping studies undertaken at different times, scales and for different purposes (Table 1) and resulting in mapping products of variable scale, style and data content were reinterpreted to achieve a consistent classification. Soil units were rated according to nutrient concentration and pH, with the many soil units without analytical assessment assigned ratings according to analysis of similar soils in adjoining surveys. Use of different scaled maps resulted in abrupt changes in the polygon size and purity at the map boundaries.

Groundwater coverage. The groundwater coverage (Table 2) assesses the likely hazard of nutrients from the deeper (>3m) groundwater that may seep into Moreton Bay and affect *L. majuscula* productivity. Geological maps (NR&M 2002), elevation data (NR&M 2005b), and data on the Fe content and hydraulic conductivity of the dominant aquifer material were used to assign ratings in the groundwater coverage (Preda & Cox 2004). Porous geological units likely to contain water and Fe-rich minerals (e.g. basalt) were given a high rating while massive rocks with little Fe (e.g. granite) were rated low.

Vegetation coverage. Data came from the Queensland Environment Protection Agency (EPA 1999a, 1999b), and was derived from both pre-clearing and remnant vegetation surveys. The dominant regional ecosystem unit within the attribute table of the vegetation GIS coverages was used for assessment purposes, with ratings assigned to each unit according to previously recorded *L. majuscula* bioassay growth responses, or other available references. Albert *et al.* (2005), Ahern *et al.* (2006a) and Ahern *et al.* (2003) all recorded

Table 3. Proximity ratings for the five nutrients used in the GIS 'proximity coverage'. For a particular nutrient, ratings are a combination of distance from the coast (columns) and distance from streams (rows).

Nutrients	Proximity rating								Moreton Bay Islands
			Distance to coast (km)						
			<5	5 to 10	10 to 20	20 to 30	30 to 50	>50	
Fe	Distance to stream (km)	>1	2	2	1.75	1.5	0.75	0.5	4
		0.5 to 1	3.2	3.2	2.8	2.4	1.2	0.8	
		<0.5	4	4	3.5	3	1.5	1	
OC	Distance to stream (km)	>1	2	2	1.75	1.5	1.1	1	4
		0.5 to 1	3.2	3.2	2.8	2.4	1.76	1.6	
		<0.5	4	4	3.5	3	2.2	2	
P	Distance to stream (km)	>1	1.1	1.1	1	1	0.85	0.75	1.98
		0.5 to 1	1.76	1.76	1.6	1.6	1.36	1.2	
		<0.5	1.98	1.98	1.8	1.8	1.53	1.35	
pH	Distance to stream (km)	>1	1.1	1.1	1	1	0.85	0.75	1.98
		0.5 to 1	1.76	1.76	1.6	1.6	1.36	1.2	
		<0.5	1.98	1.98	1.8	1.8	1.53	1.35	
N	Distance to stream (km)	>1	1.1	1.1	1	1	0.85	0.75	1.98
		0.5 to 1	1.76	1.76	1.6	1.6	1.36	1.2	
		<0.5	1.98	1.98	1.8	1.8	1.53	1.35	

positive *L. majuscula* responses to diluted soil extracts or shallow groundwater taken from vegetation communities containing *Melaleuca*, *Casuarina*, or pine plantations. As a result, regional ecosystems with these species received the highest rating compared to those without these species.

In the early stages of model development, only the remnant vegetation map was used. However, as much of the vegetation in the study area has been cleared, this resulted in a potential bias to the areas where vegetation remains. Therefore, in the current model, both pre-cleared vegetation and remnant vegetation layers were included, with a weighting of 0.5 for each.

Coast and stream proximity coverage. This was developed to allow greater emphasis to be placed on nutrient sources closer to streams and rivers (<0.5km; 0.5–1.0km; >1.0km from streams). Distance from the coast (<5; 5–10; 10–20; 20–30; 30–50; >50km) was included to broadly reflect the distance nutrients had to travel to estuaries and near shore marine locations, and the influence this may have on bio-availability at the destination. These two coverages were used to produce a 'proximity coverage' with values allocated to the combination of categories (Table 3).

Factors affecting nutrient transport and bio-availability are complex, and depend on interactions involving oxidation, pH, salinity, temperature, amount of water mixing, and time. As a result different proximity values (Table 3) were needed for some nutrients. For example, ferrous Fe (the most soluble inorganic form of Fe) rapidly oxidises in aerated water and generally forms precipitates of ferric oxyhydroxides, particularly as acidity decreases. These Fe precipitates may still be transported into estuaries and near-shore marine environments, but studies suggest that precipitated Fe, and the Fe oxides common in particles eroded from soils, are virtually unavailable for uptake by *L. majuscula*. Therefore, lower Fe proximity values were allocated to polygons

Table 4. Some brief examples of attribute tables from four of the GIS coverages, showing the addition of hazard ratings for each of the five nutrients. A rating of 1 is low or unknown, 2 is medium, 3 is high and 4 is very high.

Layer	Attribute code	Description	Nutrient hazard ratings				
			Fe	P	OC	N	pH
Soils	P	Lithosols sandy (Rudosol)	1	1	1	1	1
	W	R-Y podzolics sedimentary (Kurosol)	2	1	1	1	2
	DE	Prairie soil (Dermosol)	3	3	1	3	1
Acid sulfate soils	A0S0	Actual acid sulfate soil	4	2	2	2	4
	A0S0W	Actual acid sulfate soil wetlands	4	3	3	3	4
Land use	3.5.4	Seasonal horticulture, vegetables and herbs	2	3	2	3	2
	5.4.2	Rural residential development	1	2	1	2	1
Vegetation	12.2.7	*Melaleuca quinquenervia* on sand plains	3	1	1	3	3
	12.2.10	*Eucalyptus* sp. and *Corymbia* sp. on dunes and sand plains	3	1	1	3	3

greater than 1 km from a stream and greater than 30 km from the coast, compared to other nutrients (Table 3) that are not subject to the same rapid oxidation effects. For example, most P is adsorbed onto soil particles, which are suspended and later deposited in the marine environment by rainfall events. The proportion of soluble P is usually low except where fertiliser is used. Soluble P is usually longer lived in solution than soluble Fe species.

RESOURCES USED TO ASSIGN HAZARD RATINGS

Literature including maps, analytical reports, journal articles and student theses, along with data from site investigations, provided most of the information used to assign hazard ratings to separate parcels of land. Site investigations involved nutrient analyses from soil cores at 74 sites (although 160 sites have now been completed), and groundwater samples (<3m) also from 74 sites. Most sampling was conducted within the boundaries of the meso-scale hazard map. It was hoped that a detailed understanding of relationships in this smaller area, would allow more accurate macro-scale extrapolation. Where information gaps persisted ratings were assigned using expert opinion. Such ratings were further reviewed and debated by an interdisciplinary group of scientists (Southeast Queensland Healthy Waterways Partnership Scientific Panel).

Analyses were conducted by the NATA registered laboratory of the Natural Resource Sciences Chemistry Centre, NRW, Brisbane. Soils were analysed for pH (1:5 water) (4A1), extractable P (9B2), extractable Fe (12A1_Fe), total carbon (6B4) and extractable N (7B1) (method numbers shown after the test refer to Rayment & Higginson, 1992). Acid sulphate soils were identified by soil profile morphology, peroxide field pH tests (Ahern *et al.* 1998) and laboratory analyses following the ASS methods of Ahern *et al.* (2004).

Shallow (<3m) groundwater samples were collected from piezometers installed by the Queensland Department of Natural Resources and Water (NRW), and analysed for pH (4500H), Electrical Conductivity (EC) (2510A), nitrate (NO_3) N (4500NO3-I), dissolved inorganic carbon (5310A), dissolved organic carbon (5310D), ammonium (NH_4^+) N (4500NH3H), phosphate (PO_4^{3-}) P (4500PG) and total N (4500Norg+4500NO3-I) (method numbers shown after the test refer to APHA-AWWA-WPCF, 2005). Statistical analyses of the groundwater analyses are given in an accompanying paper (Ahern *et al.* 2008b).

MODELLING PROCESS

The aim was to calculate a numerical hazard rating for each polygon in the final GIS based model coverage. The extensive modelling process, (summarised in Figs 1 and 2) involved a complex series of steps. To assist understanding, the steps (for Fe) are detailed below.

Step 1. *Assign Fe hazard rating to attribute table.* Fe hazard ratings are added to the attribute tables of the six coverages (ASS, landuse, soil, groundwater, pre-clearing vegetation and remnant vegetation). Each of the existing GIS coverages was a vector coverage, with its own associated tables containing descriptions and attribute codes for each polygon. Based on the information resources described earlier, and the attribute itself, an individual hazard rating (on a scale of

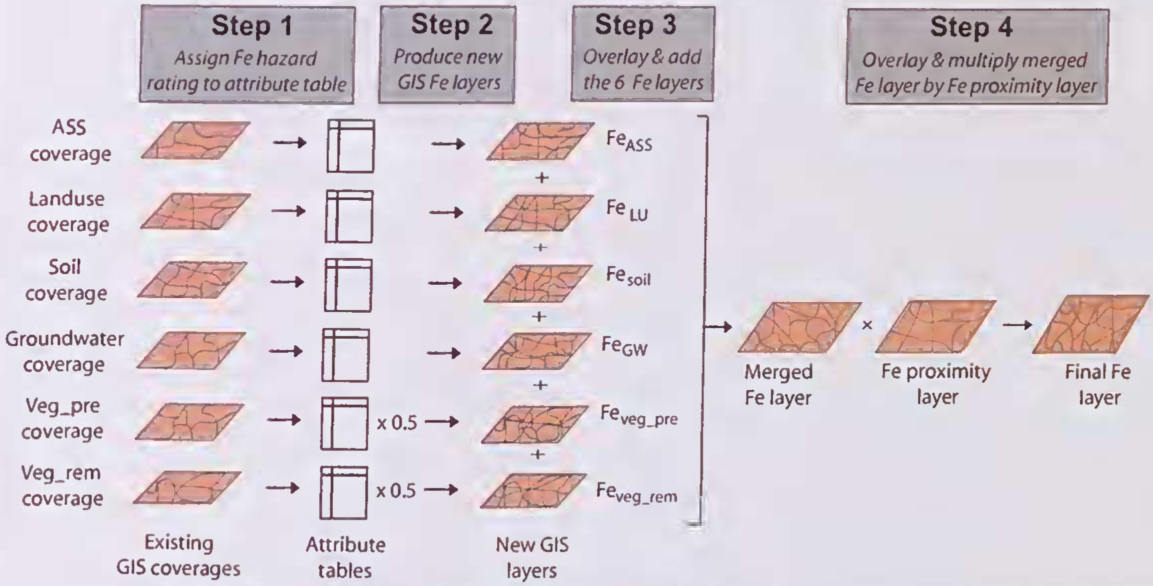

FIG. 1. Diagrammatic representation of steps 1–4 of the nutrient hazard model, (using iron as the example).

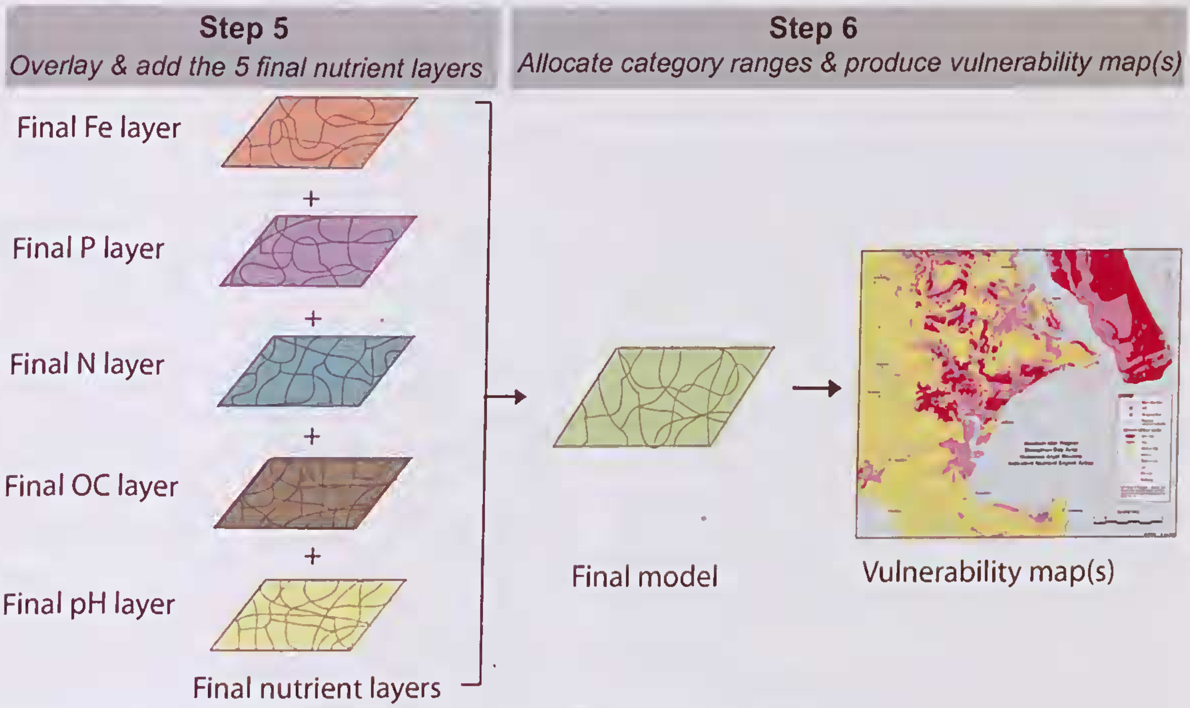

FIG. 2. Diagrammatic representation of steps 5–6 of the nutrient hazard model.

1 to 4) for Fe is allocated to the polygon table to produce an extended attribute table for each coverage (see examples in Table 4). Hazard ratings are based on the potential of a particular parcel of land (polygon) to deliver a nutrient for transport: 1 = low (or unknown); 2 = medium; 3 = high; and 4 = very high (a rating of 4 is restricted to extreme areas, e.g. actual ASS areas where field pH is <4.0).

Step 2. *Produce six new GIS Fe layers.* New Fe coverages are produced for ASS (Fe_{ASS}), landuse (Fe_{LU}), soil (Fe_{Soil}), groundwater (Fe_{GW}), pre-clearing vegetation ($Fe_{Veg\text{-}pre}$), and remnant vegetation ($Fe_{Veg\text{-}rem}$). These consist of the original polygon boundaries, but with added values of 1 to 4 (taken from the extended attribute table). The software dissolves boundaries between adjoining polygons with the same numeric value to produce a new layer with a reduced number of polygons (Fig. 1). Note the Fe hazard rating in the attribute tables of two vegetation coverages is multiplied by 0.5 to give values of 0.5–2. This gave the overall weighting of 1.0 for the sum of both vegetation coverages as discussed earlier.

Step 3. *Overlay and add the six Fe layers.* A new merged Fe layer is produced by overlaying the six new GIS Fe layers produced in step 2. Boundaries between adjoining polygons with the same numeric value are dissolved to produce a new merged Fe layer.

Step 4. *Overlay and multiply the merged Fe layer and the Fe proximity layer.* The merged Fe layer is overlaid and multiplied by the proximity factor layer for Fe (PF_{Fe}) to produce another Fe layer. Boundaries are dissolved between adjoining polygons with the same numeric value to produce a final Fe layer which thus takes into account all GIS coverages as well as proximity to coasts and streams.

The process described for Fe in steps 1 to 4 is repeated for the remaining four nutrients, resulting in five final nutrient layers (Fe, P, N, OC, pH) that have been merged and multiplied by their corresponding proximity coverage. The program creating the model conducts these steps sequentially once all the hazard ratings are entered in the attribute tables of the initial coverages.

Step 5. *Overlay and add the five final nutrient layers.* The five final nutrient layers (Fe, P, N, OC, pH) are overlaid on each other (Fig. 2) and the values are added to give a new combined nutrient layer. Boundaries are dissolved between adjoining polygons with the same numeric value to produce the 'final model' (a GIS coverage with numeric hazard values for each final polygon).

Step 6. *Allocate category ranges and produce hazard map(s).* Category ranges are allocated in the numeric model. Colours are selected to display each category range and then nutrient hazard maps are produced (Fig. 3).

RESULTS AND DISCUSSION

MESO-SCALE MAP

The map (Fig. 3) highlights that the high and very high nutrient hazard areas (coloured pink and red) generally coincide with actual ASS, potential ASS, pine plantations, soils with elevated Fe concentrations, vegetation communities containing *Melaleuca* and *Casuarina* species, and the highly transmissive sandy soils of Bribie Island and the coastal lowlands. Extensive soil (160 sites) and water (74 piezometers) sampling has been conducted in this area, and while some data were available during the model development phase, most have been produced recently and has been useful to compare with model outputs.

The model output map (Fig. 3) also reflects the results of both the extensive soil sampling program (Pointon *et al.* 2007), and the shallow groundwater sampling (Ahern *et al.* 2008b, this volume), and shows some limited areas of *Melaleuca*, and an appreciable area of pine plantations, as only rated medium high (orange colour Fig. 3). *Algal Blooms* policy 2.4.7 (EPA 2006) only emphasises caution with high and very high categories. Groundwaters and some soil extracts from pine plantations, *Melaleuca* and ASS have shown significant responses when a small amount was added to *L. majuscula* bioassays in seawater (Ahern *et al.* 2006a; Albert *et al.* 2005; Ahern *et al.* 2003). In-situ experiments in Moreton Bay (Ahern *et al.* 2007a) show such laboratory results are transferable to natural situations. Additionally, highly significant *L. majuscula* responses to added Fe, P and N in both laboratory bioassays and *in situ* field experiments (e.g. Ahern *et al.* 2008a; Ahern *et al.* 2007a), strengthen the importance of rating areas high in

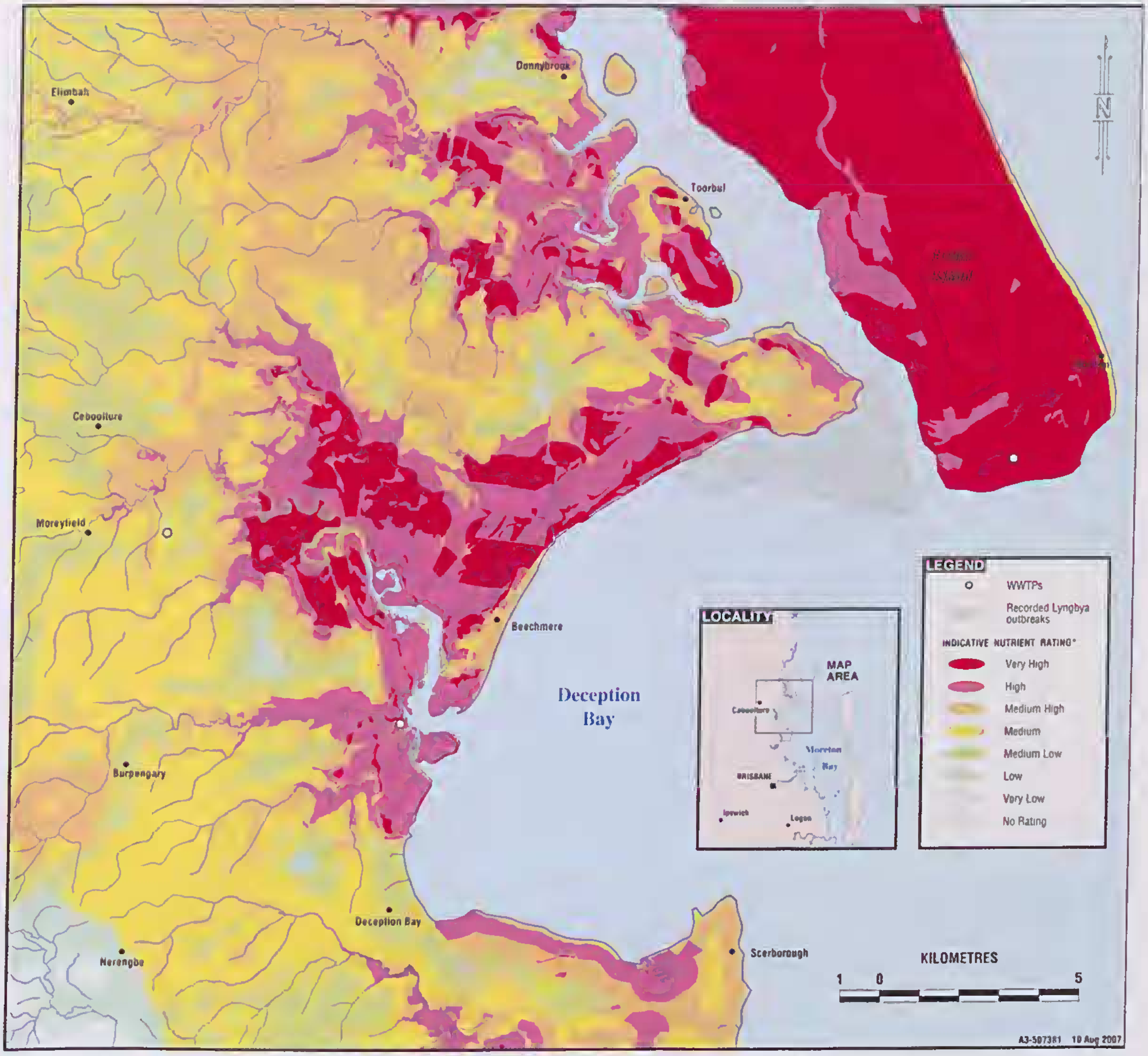

FIG. 3. Meso-scale nutrient hazard map of the Deception Bay and southern Pumicestone Passage area.

these nutrients as a hazard. Ahern *et al.* (2008b, this volume) also shows Fe, organics or P in groundwaters from these areas to be appreciable. Therefore, we added a high rating to areas of pine plantations, *Melaleuca* and ASS, not already rated high or very high in Figure 3, and produced a nutrient hazard map (Fig. 4) for use by planners and managers to assist decision making.

MACRO-SCALE MAP

The macro-scale map (Fig. 5) indicates those areas most vulnerable to the supply and delivery of relevant nutrients to the coast, are the sand islands of Moreton Bay, the horticulture, agriculture and ASS areas of the Logan, Caboolture, Maroochy and Mooloolaba Rivers, and the pine plantation areas adjacent to Pumicestone Passage. The methods used in the modelling process provide a means of combining the information from all the different layers, giving a cumulative nutrient hazard rating.

LIMITATIONS OF GIS AND MODELLING APPROACH

In developing the model, some challenging issues were encountered with GIS coverages

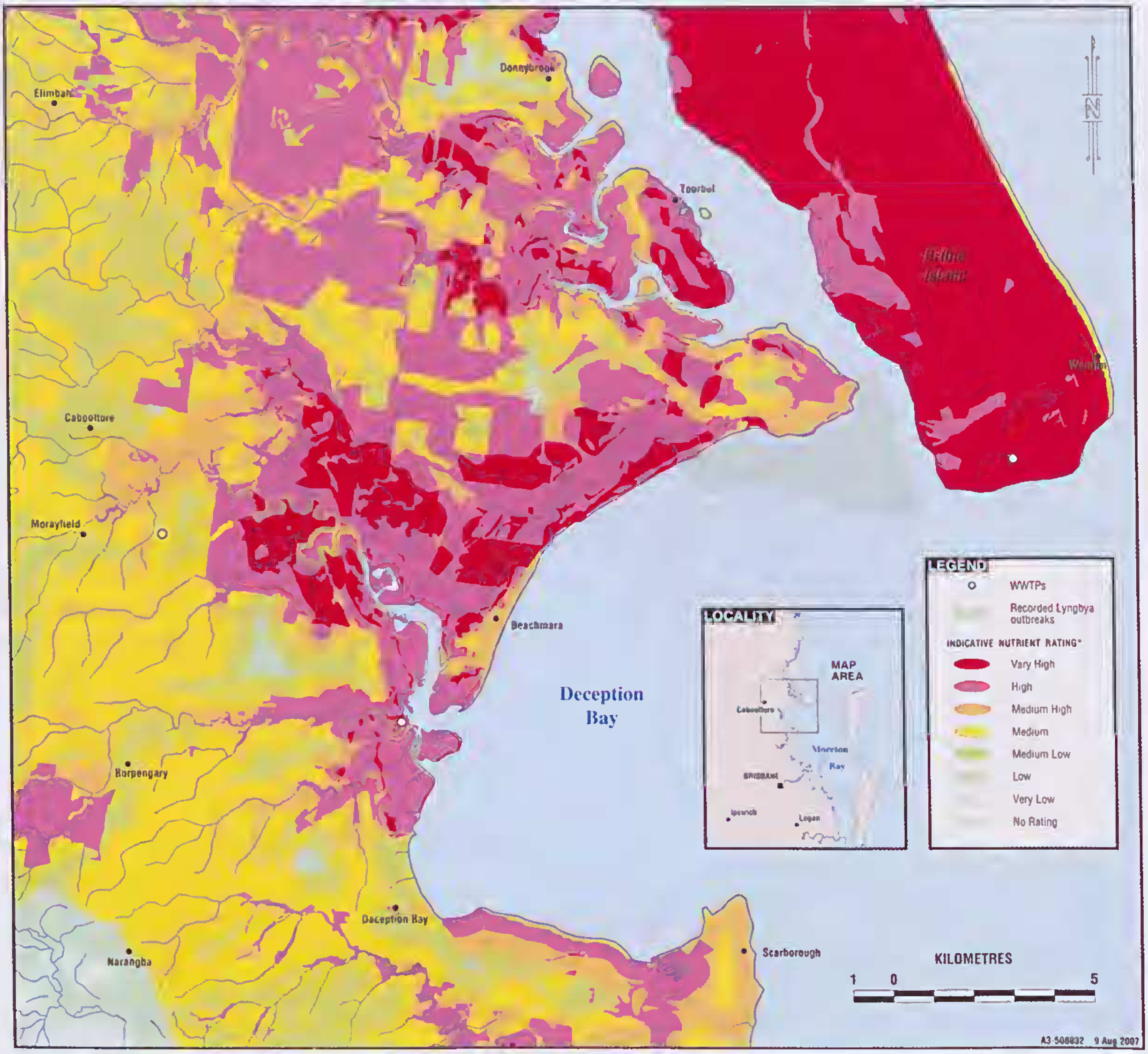

FIG. 4. Meso-scale nutrient hazard map of the Deception Bay and southern Pumicestone Passage area including the addition of pine plantations, Melaleuca, and ASS.

such as different map scales (1:25 000 to 1:2 000 000 for soils), different coastal boundaries and different methods of mapping. For example, vegetation coverages extend beyond highest astronomical tide (HAT) to low water mark where mangroves and other salt tolerant vegetation grow, while landuse and soil coverages commonly use high tide mark or HAT. Differences in scale, or gaps in coverages, can also be an issue. The eastern edge of Bribie Island, and the southern Deception Bay area of Rothwell and Kippa-Ring, display some of these GIS issues (Fig. 3).

The final model represents the combined impact of all factors likely to influence nutrient export from land sources. A limitation with the spatial method of representation is that it cannot easily represent the relative importance of major nutrient point sources (e.g. sewage treatment plants) due to their small spatial extent. Also, there is no represention of areas using septic systems rather than reticulated sewage. This would be a useful addition to future projects, as septic systems supply considerable amounts of labile nutrients to the groundwater

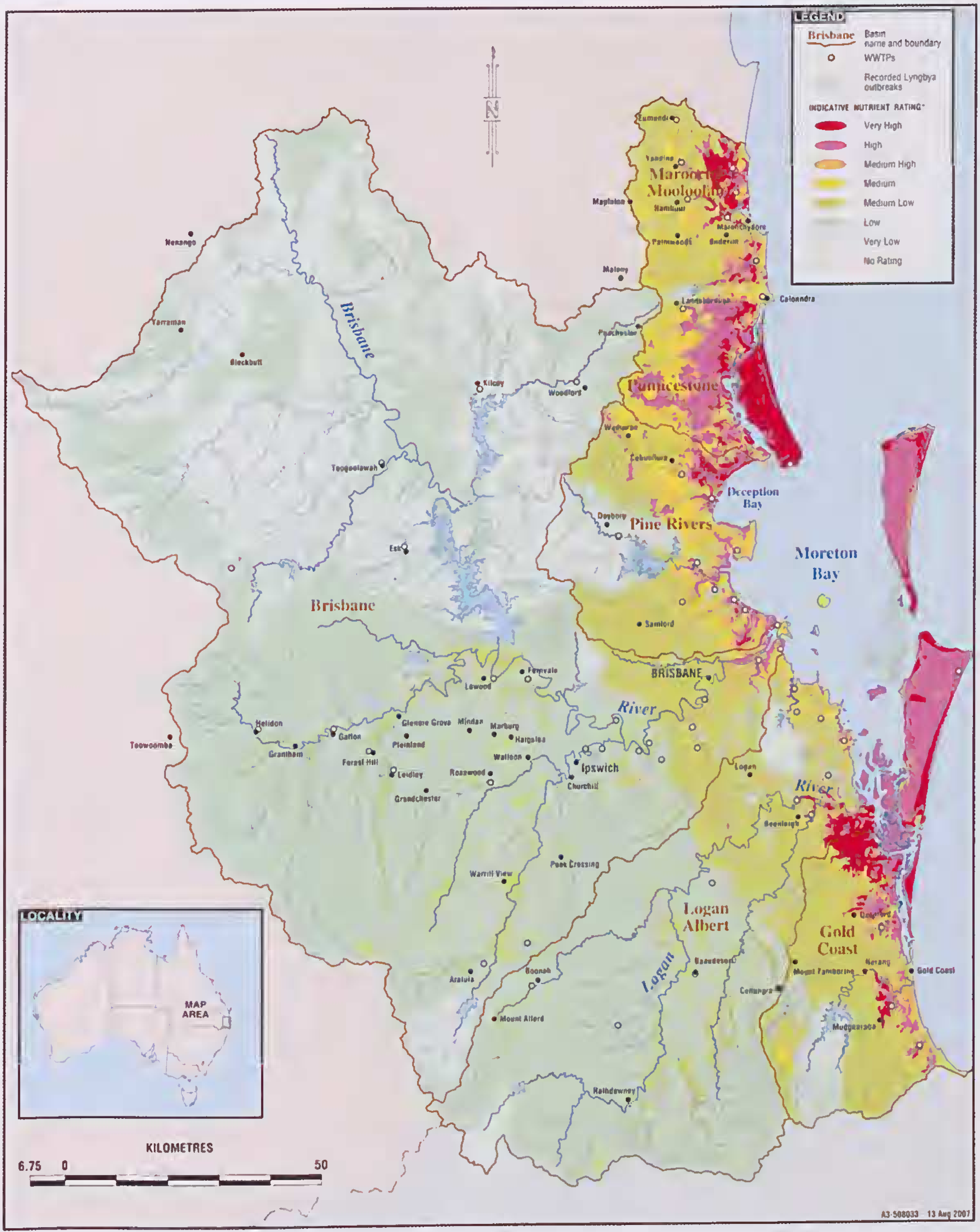

FIG. 5. Macro-scale indicative nutrient hazard map of Southeast Queensland including the addition of pine plantations, *Melaleuca*, and ASS.

(Whitehead *et al.* 2003). Finally, a model is only as good as its data sources, and so it is highly recommended that the 1999 land use coverage be updated to reflect the many land use changes that have since taken place in southeast Queensland.

A major benefit of this technique is that the model can be re-run, and new maps produced, as new information and updated coverages become available. Within the model, heavy emphasis has been placed on the transport mechanism ('coastal and stream proximity' layer), since it is only when the nutrients reach the shallow coastal and estuarine waters of Moreton Bay that they can contribute to the growth of *L. majuscula*. The results of this emphasis can be seen in the meso-scale map (Fig. 4), where areas >1km from streams have a lower rating.

Information being gathered regarding *L. majuscula* growth factors has been used in Bayesian modeling (Hamilton *et al.* 2005). Future developments will be to combine or replace the proximity coverage with sediment and nutrient run-off models such as E2 (eWater Cooperative Research Centre, Canberra). Such a project is under consideration for future funding.

CONCLUSION

Southeast Queensland's fast growing population is forcing significant land use changes. Resultant disturbance and changes to drainage patterns will continue to affect the supply and delivery of nutrients to the waters of Moreton Bay. The model and resulting maps from this investigation provide an assessment as to where to concentrate efforts to limit or reduce the 'nutrients of concern' that contribute to blooms of *L. majuscula*.

Maps from the earlier version of the model were incorporated as tools into the *Algal Blooms* policy 2.4.7 in the *Southeast Queensland Regional Coastal Management Plan* (EPA 2006). Subsequent research and further soil sampling continue to support the findings displayed in the original maps. Fine tuning of the model has resulted in new nutrient hazard maps (Figs 4, 5), and although similar to the early versions, these new maps provide an update.

Appropriate nutrient management guidelines need to be developed for industry use when disturbing areas rated high or very high in the nutrient hazard maps.

ACKNOWLEDGEMENTS

The authors acknowledge the funding support from the Queensland Environmental Protection Agency, Southeast Queensland Healthy Waterways Partnership and the Department of Natural Resources and Water. I. Hall, J. Manders and L. O'Brien (Queensland Department of Natural Resources and Water) for assistance with the installation of piezometers, soil and water sampling. D. Lyons, S. Mork, R. Turner and staff at the Natural Resource Sciences Chemistry Centre, NRW undertook laboratory analysis of groundwaters and soils. Malcolm Cox, Queensland University of Technology assisted with compilation of the groundwater coverage. For helpful comments on the manuscript we acknowledge B. Powell and L. O'Brien (Queensland Department of Natural Resources and Water).

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